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Tuneable IR Photodetectors for Spectroscopic Applications

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Abstract

The concept and realisation of infrared micro-spectrometers using MEMS based Fabry-Pérot micro-filters integrated with IR photo-detectors are presented. By using five layer mirror structures, and stress optimisation in mirrors and actuators the tuning range from 1700nm to 2300nm has been achieved with maximum actuation voltage of only 18V RMS. The average FWHM of the transmission peak was measured to be 35nm, predominantly limited by thickness nonuniformity of individual mirror layers.

Keywords: IR microspectrometers, MEMS, tuneable IR detectors

1. Introduction

New emerging applications of infrared detectors require the detection of narrow spectral lines allowing the identification of various gases and chemicals present in the scene. At present, infrared spectrometers are bulky, expensive and hence unsuitable for many field applications. Also, the operation of most current infrared (IR) photo-detectors is still based on integrated intensity signal over a broad range of wavelengths resulting in a loss of a significant amount of colour-like information. Consequently, there is an increasing international research effort into development of inexpensive and miniature IR spectrometers.

2. Device design and fabrication

The investigated here micro-spectrometers are based on integration of IR photo-detectors with Fabry-Pérot micro-filters fabricated using surface micromachining (MEMS) technology [1, 2]. InGaAs and HgCdTe photodetectors are typically used for near (1500-2500nm) and mid-wave (3000-5000nm) ranges respectively. The MEMS based micro-filters are fabricated using low temperature (~200^{0}C) SiN_x as structural and isolation material and also as low refractive index layer in Ge/SiN_x based Bragg mirrors of the Fabry-Pérot micro-filter. The structure of the single device is shown in Fig.1.a. The design consists of two mirrors separated by the air gap defining the tuning range. The mirrors are made of five alternating layers of Ge and SiN_x. Ge is thermally (or E-beam) evaporated, and SiN_x deposited using plasma enhanced chemical vapor deposition (PECVD). The thickness of layers is optimized at the middle of the selected operational spectral range (2000nm in this case).

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Bottom mirror is deposited directly on the silicon wafer, while the top one is suspended on doubly clamped actuators covered with thin gold layer acting as top electrode for electrostatic actuation. The bottom electrode covers entire area available on a die except the aperture located under the top mirror. It also serves as a shield for stray light bypassing the filter.

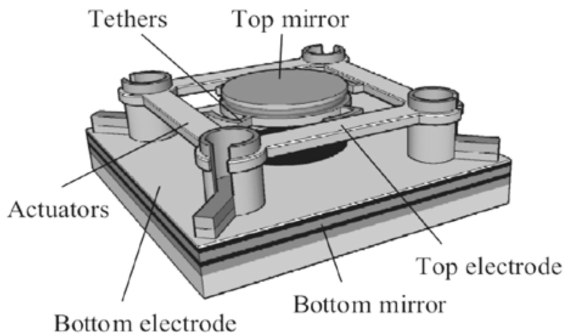


Fig 1: MEMS based micro-Fabry-Pérot IR filter. Top Bragg mirror is suspended on doubly clamped actuators which are supported by four cylindrical connectors. The split in these connectors is needed for continuity of the gold layer between bottom and top level of the device. The black round shape under the top mirror is the aperture in the bottom gold electrode.

3. Device characterisation

Fig. 2 shows optical profilometer image of the real device. Note, that due to optical transparency of the tethers, they artificially appear at the bottom of the structure. In as fabricated device, the top mirror shows significant bowing due to thermal stress and stress gradient in Ge and SiN_x layers which leads to significant increase of FWHM. It is possible to reduce this bowing by introducing additional thin SiN_x layer, on top or at the bottom of the top mirror, with its stress tuned to balance the overall stress in the mirror. However, this approach requires very high deposition precision which is available in a dedicated fabrication facility, but rather difficult to maintain in a typical research laboratory where PECVD system is usually used for different processes. The alternative and more practical approach is annealing of the stressed structure. In our study micro-filters were subjected to relatively low temperature annealing (or baking) in air on standard hotplate. Such annealing was performed in timed stages checking the profile of the structure after each stage using optical profilometer. Application of this simple process can remove the original bowing almost completely as shown in the optical profilometer image in Fig.2. The flatness of the top mirror extracted from this scan is of the order of 10nm to 20nm with the diameter of the top mirror being 100μm. The evolution of the profile across the structure during baking is presented in Fig.3. Practically flat mirror was obtained after 10 minutes baking at 260^0C. It has to be noted however, that although the stress removal by annealing procedure works perfectly for investigated here Ge/SiN_x 5 layer structure, it may not work so well if different materials are used.

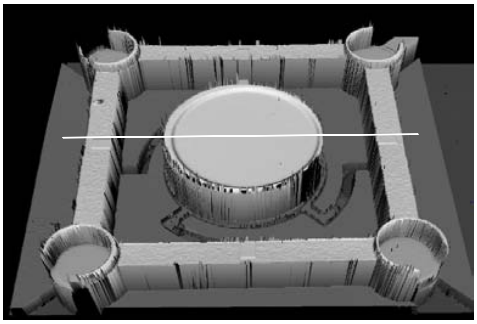


Fig. 2. Optical profilometer (Zygo) 3D scan of the real device. The tethers made of SiN_x and connecting the top mirror structure with doubly clamped actuators appear artificially at the bottom due to their optical transparency. The profiles shown in Fig.3 were taken along the horizontal line.

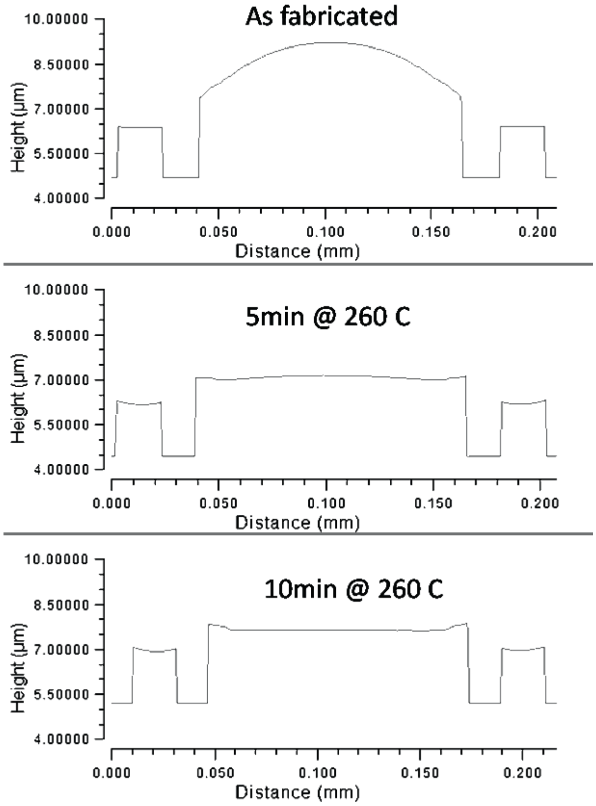
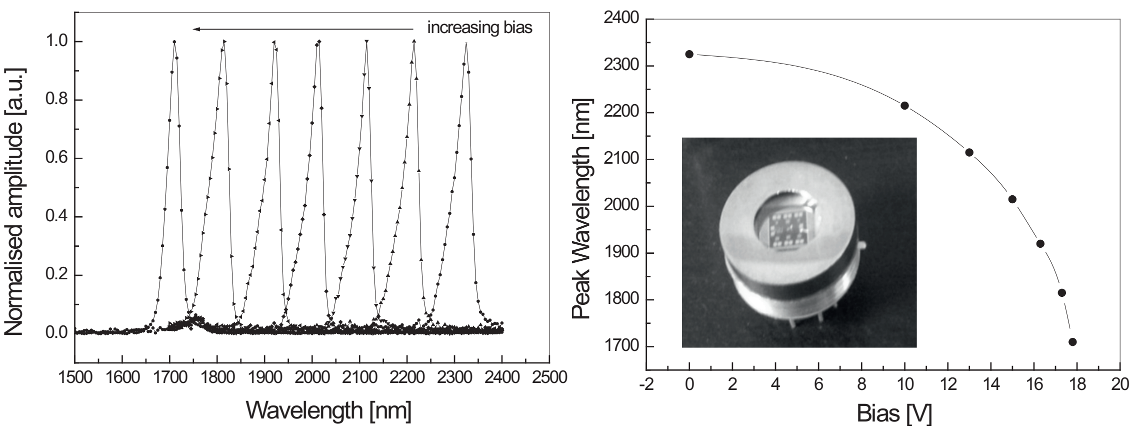


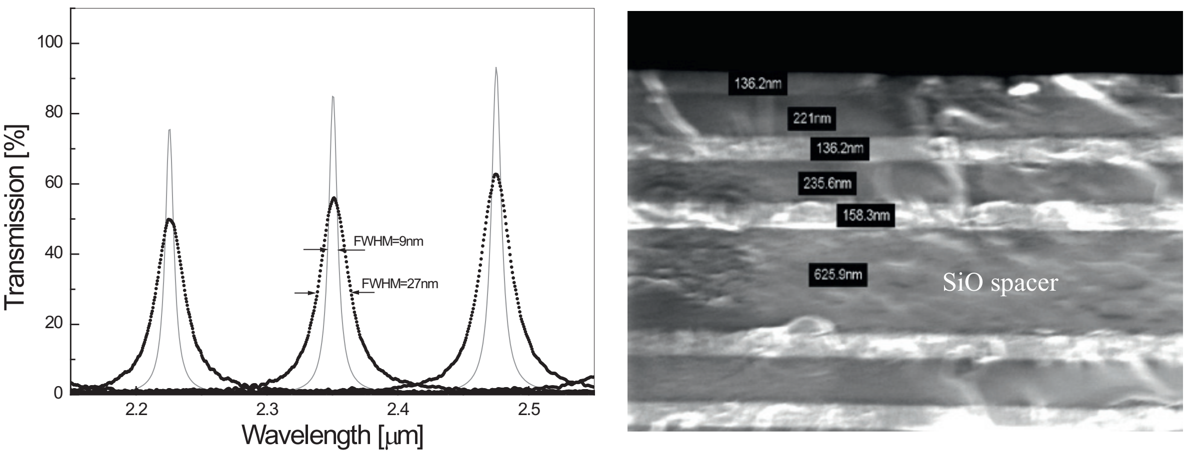
Fig. 3. The profile of the micro-spectrometer device at various stages of baking. These profiles were taken along the line indicated in Fig.2.

Fig. 4.a shows the optical spectra of a typical completely integrated device enclosed in dry nitrogen filled TO8 package with sapphire window (insert in Figure 4.b.) The tuning range extends from 1700nm to 2300nm with average FWHM around 35nm. It is important to note the low bias (only 18V RMS) required for electrostatic actuation. The tuning range of the device is defined by the maximum possible actuator deflection before snap down caused be the build-up of charge on electrodes. This effect can be observed in Fig.4.b in the form of highly nonlinear characteristic of the filter's transmission wavelength as a function of applied bias. The analysis of the peaks shape indicates that the main contribution to their broadening comes from the layers nonuniformity and to much less extent from top mirror bowing. In Fig. 5.a the experimental spectra of a fixed Ge/SiO based



a) b)

Fig 4: a) Normalized (to max. of the peak) detector signal as a function of wavelength with 100kHz square wave AC bias increasing from 0V to 18V (RMS) showing tuning range from 2300nm to 1700nm. b) Position of the filter's transmission peak as a function of applied bias showing strongly nonlinear characteristic limited by the snap down effect at around 18V RMS. The inset shows complete device in TO8 package.



a) b)

Figure 3. a) Experimental (dark points) and theoretical (light gray line) transmission spectra for fixed Fabry-Pérot filters. In the middle of the range the experimental FWHM of 27nm is three times larger than theoretical value of 9nm; b) SEM picture of the cleaved fixed filter structure. Darker layers – SiO, brighter – Ge. The thickness of individual layers in top mirror (in nm), starting from top Ge is: 136/221/136/235/158.

filter with bottom and top mirror separated by the layer of SiO were deposited on 300 µm thick silicon wafer. Their FWHM found to be 27nm at ~2.35µm is not significantly better than 35nm obtained for tunable micro-spectrometer although the whole structure of the fixed filter, deposited on silicon wafer, is almost perfectly flat. In addition the theoretical modeling, shown as the thin line in Fig.5.a, gives only ~9nm. The answer for the discrepancy comes from the SEM picture of the cleaved fixed filter. The thickness of the individual layers in not very uniform, a consequence of limited accuracy of thickness monitor. The interface roughness is also clearly visible. It is expected that the uniformity of the Ge/SiN_x based mirrors is similar. Consequently, in order to achieve next stage of FWHM improvement, much more accurate control of the deposition process is required particularly better control of the thickness. The smaller effect of asymmetry of the peaks (peaks extending towards shorter wavelengths in Fig. 5.a) is caused by remaining bowing of the top mirror which has been confirmed by analysis of the optical profilometer data.

3. Conclusions

The characteristics of potentially very cheap IR micro-spectrometer, based on the hybridisation of IR photodetector with MEMS based Fabry-Pérot micro-filter, demonstrate large tuning range, low tuning voltage, and FWHM of the transmission peak satisfying wide range of practical applications.

Acknowledgements

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